

WIND FORCING OF THE PACIFIC OCEAN USING SCATTEROMETER WIND DATA

Final Report, Summary of Research

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1 Goals

The long-term objective of this research was an understanding of the wind-forced ocean circulation, particularly for the Pacific Ocean. To determine the ocean's response to the winds, we first needed to generate accurate maps of wind stress. For the ocean's response to wind stress we examined the sea surface height (SSH) both from altimeters and from numerical models for the Pacific Ocean.

2 Results

An integrated program was conducted to design a methodology for mapping scatterometer winds and to create fields of wind stress, to evaluate the accuracy of scatterometer winds, mapped wind fields, and wind products derived from the maps, and to evaluate ocean simulations forced by the winds. Comparisons of scatterometer vectors from NSCAT with Tropical Atmosphere-Ocean (TAO) buoy winds were used to assess wind vector and map accuracy and to investigate possible corrections, particularly for errors due to precipitation. The scatterometer maps were compared both directly with conventional wind products, and by simulations of the response of the Pacific Ocean to evaluate differences in the fields.

2.1 Map Methodology and Ocean Response in the North Pacific Ocean

Prior to the launch of NSCAT, studies were conducted both to develop a mapping procedure and to examine the response of the ocean to wind-forcing using available wind products. An optimal interpolation method for scatterometer data was developed and the statistics of the maps were examined in Kelly and Caruso (1990). One of the areas which we examined in

detail was the California Current, where we demonstrated that wind stress curl (through Ekman pumping) is responsible for seasonal changes in the current structure (Kelly et al., 1993), but that wind analysis products do not have sufficient spatial resolution to give a conclusive answer (Caruso et al., 1997).

Another study was conducted comparing the response of the ocean model developed by Harley Hurlburt to wind forcing by ECMWF and by ERS-1 winds. This study showed that the scatterometer winds gave a more realistic spatial structure in the currents than the ECMWF winds, particularly in the California Current. However, the Naval Research Laboratory researchers felt that the ECMWF winds gave better results overall due to the higher wind speeds of the 1000-mb winds.

2.2 Tropical ocean wind maps from NSCAT data

This was a collaborative project with Michael McPhaden of the Pacific Marine Environmental Laboratory (PMEL/NOAA), and Sandipa Singh of the Woods Hole Oceanographic Institution (WHOI).

The issue of mapping the scatterometer data was revisited just prior to the launch of NSCAT. The primary challenge in mapping scatterometer data is that the winds (or wind stresses) decorrelate too rapidly (24-48 hours) compared with the repeat sampling interval (two days). To generate maps optimizing both the accuracy and the resolution, we spatially decimated the data to approximately 2° resolution and then objectively mapped the decimated wind in time using the method of Chelton and Schlax (1991). In addition, because the data must be temporally averaged to make the maps, we first converted the winds to stress, to avoid a systematic underestimate of stress in the maps.

Although an objective method generates an error map, a primary concern in mapping data from satellites, which have a slowly repeating sampling pattern, is that sampling errors due to the repeat pattern can appear as realistic features of the mapped field. To minimize this aliasing problem, the expected error from the objective map needs to be relatively free of the sampling pattern (Greenslade et al., 1997; Chelton and Schlax, 1994); this was achieved for NSCAT maps of the tropical Pacific by requiring that the [spatial] standard deviation of the expected errors be less than 10% of the [spatial] mean error. This relatively conservative criterion resulted in maps with a spatial resolution of 2° and a nominal temporal resolution of 5 days, although 13 days of data are used for each map.

The following is from the abstract of a APL technical report on mapping NSCAT winds for the tropical Pacific Ocean.

Establishing a mapping methodology for NSCAT winds

S. Dickinson, S. Singh, K.A. Kelly, M. Spillane, and M. J. McPhaden

A methodology is presented for mapping swath-oriented NASA scatterometer (NSCAT) wind data into gridded maps, suitable for forcing ocean circulation

models. The NSCAT samples the winds over the equatorial Pacific Ocean unevenly in both space and time and care must be taken in mapping them onto a grid to prevent aliasing the fields. It was necessary to develop a “true” wind field with which to test the mapping methodology. Prior to NSCAT data availability, the ECMWF (European Centre for Medium-Range Weather Forecasts) and FNMOC (Fleet Numerical Meteorology and Oceanography Center) analysis wind fields were studied. Spectral analysis of the ECMWF and FNMOC wind fields showed a drastic drop in energy at frequencies higher than 600km. These energy levels were “pumped up” in the Fourier domain to more accurately represent a true wind field. These “true” wind fields were converted to pseudostress, subsampled with the known NSCAT sampling pattern (termed “synthetic NSCAT” winds) and then objectively averaged. A study of the expected errors of the mapped pseudostress was conducted using a covariance function of the equatorial Pacific wind field determined with the data from the Tropical Atmosphere Ocean (TAO) buoy array. A 5-day, 2degree resolution for the daily mapped pseudostress was chosen. Comparisons of the “true” winds converted to pseudostress and the mapped synthetic NSCAT pseudostress show errors consistent with the expected values (Figure 1). Maps made of actual NSCAT data are also presented and discussed.

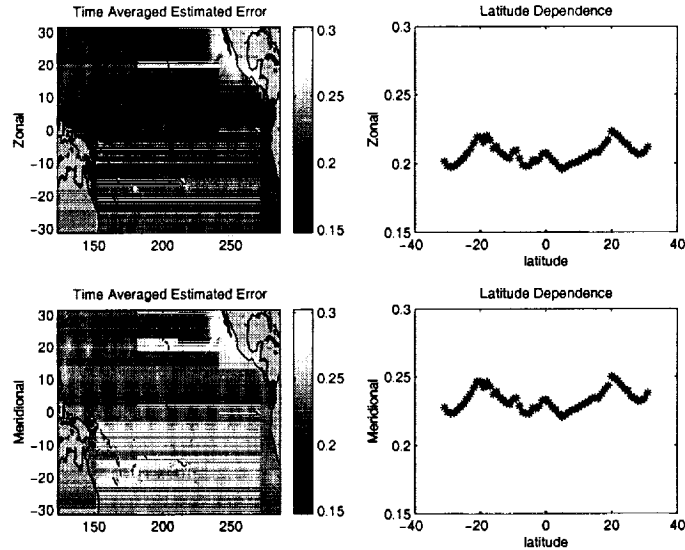


Figure 1: Normalized estimated errors, time averaged over the 8-month data set of NSCAT. Left panels show errors over the basin (normalized by the signal variance) for zonal and meridional pseudostress, respectively. Right panels show these errors (zonally averaged) as a function of latitude. (Figure 15 from *Establishing a mapping methodology for NSCAT winds*.)

A comparison between the NSCAT and ECMWF stress maps for the tropical Pacific (Kelly

et al., 1999) showed pronounced differences, particularly near the Intertropical Convergence Zone (ITCZ), see Figure 2. In this region, Rossby waves are damped so that the dominant oceanic response to winds is that of local (stationary) Ekman pumping (Kessler, 1990). The dominance of the local Ekman pumping response was also seen in previous NSCAT-sponsored analyses in the California Current (Kelly et al., 1993). The precipitation contamination in this region, although relatively small compared with the differences between ECMWF and NSCAT stresses, suggests that this issue needed to be re-examined with a precipitation correction.

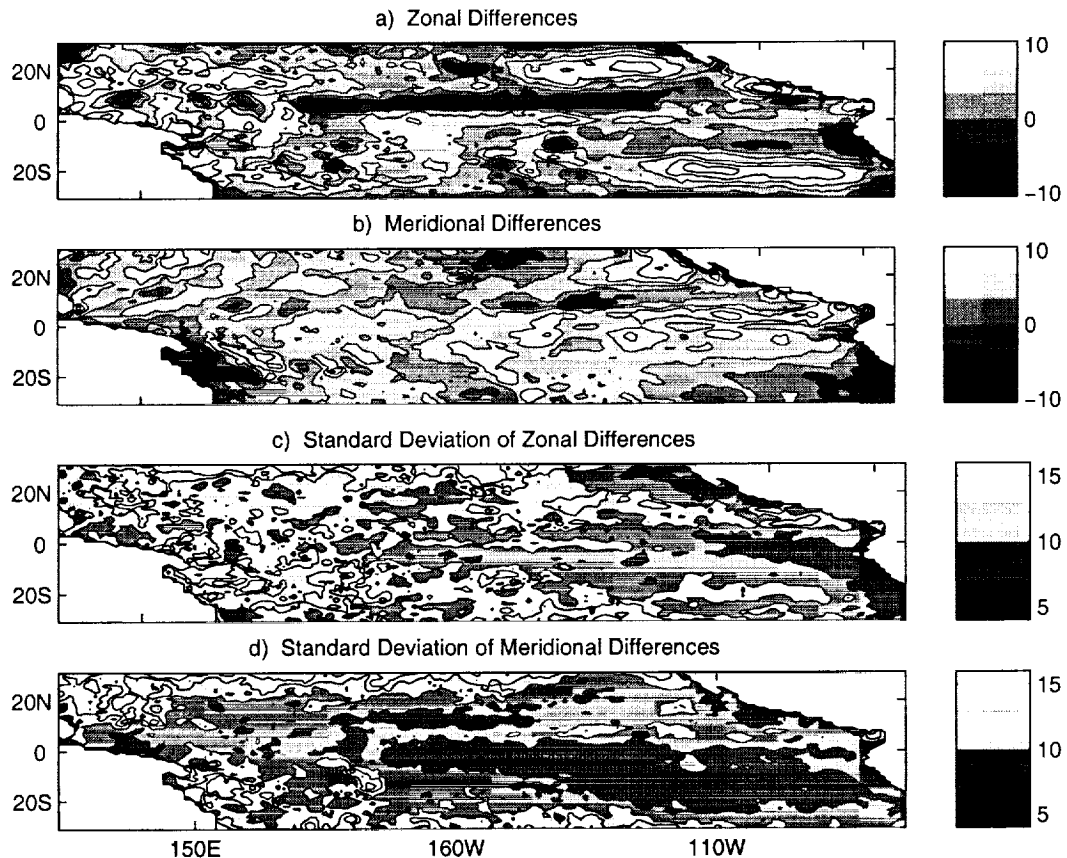


Figure 2: Differences between NSCAT and ECMWF pseudostress components, averaged over 8 months. Mean differences in (a) zonal component and (b) meridional component, NSCAT minus ECMWF, and standard deviation of the differences in (c) zonal component and (d) meridional component. Units are $m^2 s^{-2}$. (Figure 4 from *NSCAT Tropical Winds Stress Maps: Implications for Improving Ocean Modeling*.)

The following is from the abstract of a manuscript published in the NSCAT special section of the *Journal of Geophysical Research - Oceans*:

NSCAT Tropical Wind Stress Maps: Implications for Improving Ocean Modeling

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Using wind vectors from the NASA scatterometer (NSCAT), daily maps of pseudostress have been constructed for the tropical Pacific Ocean and compared with pseudostress maps derived from the European Centre for Medium-range Weather Forecasts (ECMWF) 10-m wind product. The map resolution for the NSCAT pseudostress maps was selected using both a statistical measure of the expected mapping errors and tests on realistic wind fields. The selected map resolution is 5 days and 2° , which minimizes residual effects from the NSCAT sampling pattern, while maximizing temporal and spatial resolution. Comparisons with the ECMWF maps showed significant differences in most regions, corresponding to mean wind speeds of $2\text{--}3\text{ m s}^{-1}$, particularly in the Intertropical Convergence Zone (ITCZ) and at 20° S and 20° N . A canonical correlation analysis between NSCAT and ECMWF fields showed a high degree of correlation of temporal variations and systematic differences in spatial structure. In the NSCAT fields the ITCZ is narrower, stronger, and is located $1\text{--}2^\circ$ latitude farther south than in the ECMWF fields (Figure 3). The high degree of correlation between the two fields suggested that “hybrid” fields can be generated. The dynamical implications of the differences in wind forcing are illustrated using estimates of the Sverdrup streamfunction and the Ekman pumping. A simple reduced-gravity, linear vorticity model, forced by both the ECMWF and hybrid winds to examine predicted differences in ocean response, showed higher skill for the NSCAT winds.

2.3 Forcing tropical ocean circulation with NSCAT winds

The wind maps described in the APL technical report were used by Z. Yu and W. Kessler at PMEL to drive an equatorial ocean circulation model. These studies suggested that the Kelvin wave response to NSCAT winds differ little from the response to ECMWF winds, primarily because these wind fields differ little on the equator. The similarity of observed and modeled winds was undoubtedly related to the availability of TAO wind observations near the equator, which are assimilated into the atmospheric GCMs.

The differences in the wind fields over the North Equatorial Countercurrent suggested a further study of an ocean model response to both wind stress and wind stress curl (Yu et al., 2000).

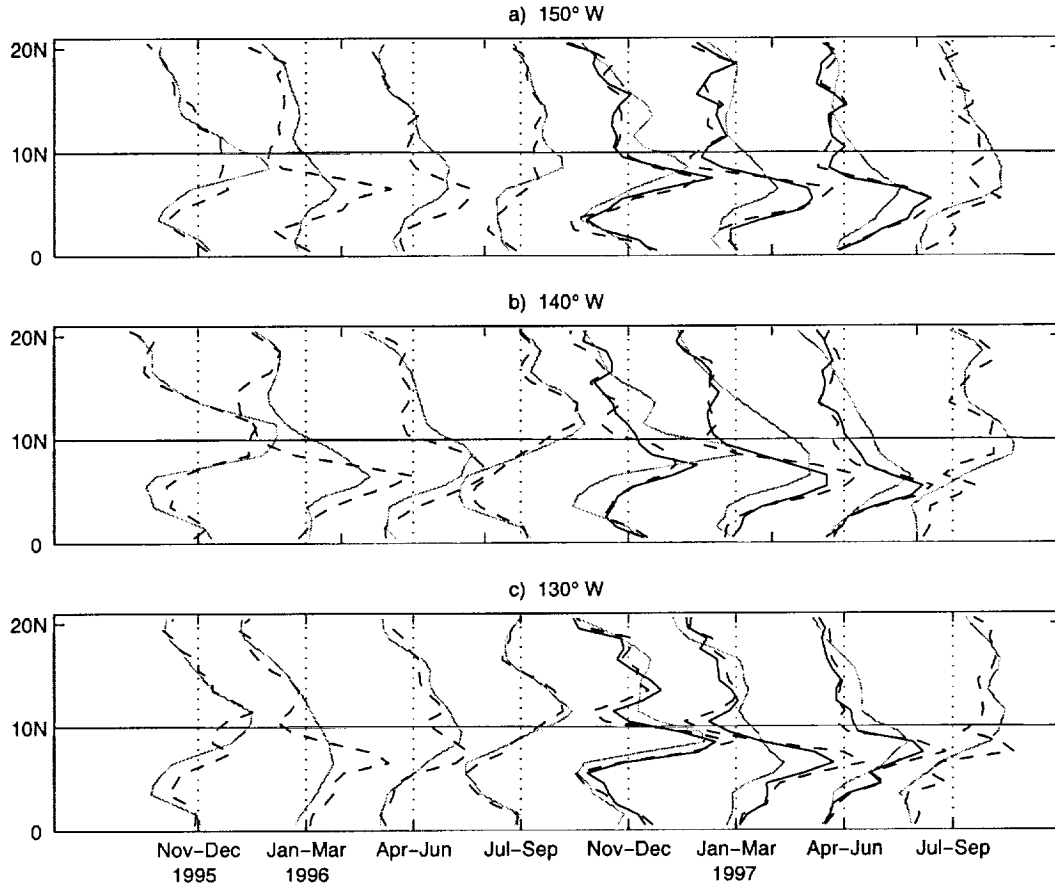


Figure 3: Profiles of seasonal wind stress curl at (a) 150°W, (b) 140°W, and (c) 130°W longitude. ECMWF are shown by stippled lines, NSCAT are solid lines and hybrid NSCAT/ECMWF are denoted by dashed lines. The zero marks of each set of three profiles shown by vertical dotted lines, are $1.5 \times 10^{-7} \text{ Nm}^{-3}$ apart. NSCAT profiles were not available before November 1996 or after June 1997. (Figure 8 (a-c only) from *NSCAT Tropical Winds Stress Maps: Implications for Improving Ocean Modeling*.)

2.4 Comparisons of scatterometer wind vectors with TAO buoy winds

This was a collaborative project with Michael Caruso of the Woods Hole Oceanographic Institution, and Michael McPhaden of the Pacific Marine Environmental Laboratory. As part of the NSCAT calibration and validation team, Kelly and co-workers collocated and compared hourly buoy winds from the TAO array with scatterometer measurements to determine the accuracy of NSCAT winds (Caruso et al., 1999). These comparisons showed an approximate 7% underestimate of the wind speeds by the NSCAT-1 model function, which was corrected to produce a negligible 1% underestimate by the NSCAT-2 model function (Dickinson et al., 2000).

A technical report was written on this subject, evaluating wind vectors using the NSCAT-1 model function, with the abstract below:

Evaluation of NSCAT scatterometer winds using equatorial Pacific buoy observations

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Linda Mangum, Michael McPhaden, and Linda Stratton, Pacific Marine Environmental Laboratory, NOAA, Seattle, WA

As part of the calibration/validation effort for NASA's Scatterometer (NSCAT) we compare the satellite data to winds measured at the sea surface with an array of buoys moored in the equatorial Pacific Ocean. The NSCAT data record runs from September, 1996 through the end of June, 1997. The raw NSCAT data, radar backscatter, is converted to wind vectors at 10 meters above the surface assuming a neutrally stratified atmosphere, using the NSCAT-1 model function. The surface winds were measured directly by the TAO (Tropical Atmosphere Ocean) buoy array spanning the width of the equatorial Pacific within about 8° of the equator. The international program for buoy servicing and their data are maintained by the Pacific Marine Environmental Labs, at the National Oceanic and Atmospheric Administration. We also use data from two buoys maintained by the Woods Hole Oceanographic Institution located along 125°W . Since the buoy winds are measured at various heights above the surface, in a real atmosphere, they are adjusted for both height and atmospheric surface layer stratification, before comparisons are made to the NSCAT data. Co-location requirements include measurements within 100 km and 60 minutes of each other. With a total of 5580 comparisons we find the NSCAT wind speeds, using the NSCAT-1 model function, are lower than the buoy wind speeds by about 0.54 m/s and have a 9.6° directional bias. The wind retrieval algorithm selects the vector closest to the buoy approximately 88% of the time. However, in the low wind speed regime of the TAO array, approximately 4% of the wind vectors are

more than 120° from the buoy wind.

A discrepancy between the TAO buoy winds and the scatterometer winds revealed an important distinction between anemometer winds and scatterometer winds, which has implications for ocean modeling. The scatterometer actually measures stress, rather than wind speed, despite its usual conversion to a 10m neutral stability wind. Thus, the scatterometer “wind” vector is actually the wind relative to the moving ocean surface, whereas an anemometer measures the wind vector relative to a fixed platform. For forcing an ocean model, or for the oceanic boundary condition for an atmospheric model, the scatterometer “wind” is actually what is needed for the stress boundary condition. Stress converted from TAO winds on buoys where currents at 10m depth are also measured showed a systematic over(under)-estimate relative to NSCAT stress, when the currents were going with (against) the winds (Dickinson et al., 2000).

In addition, the comparison of NSCAT with tropical buoy winds showed an apparent contamination by precipitation near the ITCZ, with overestimates of stress by approximately 20% for regions with monthly average rain rates of 10mm per day (Dickinson et al., 2000), see Figure 4.

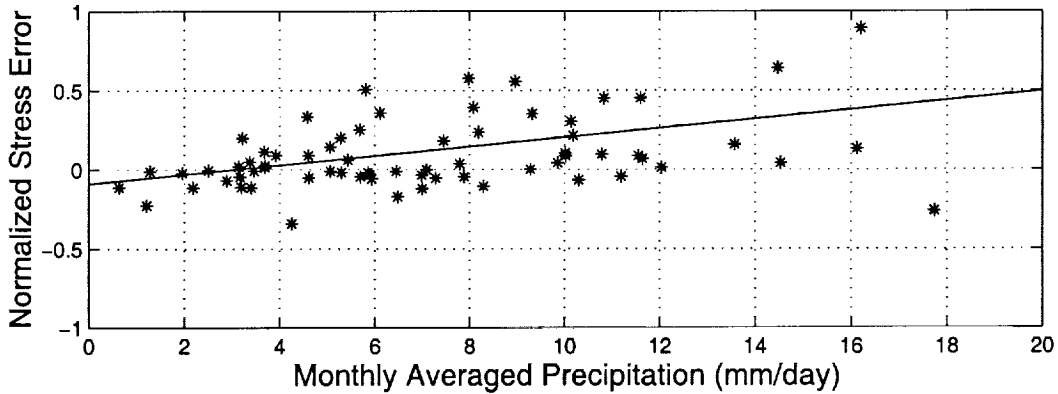
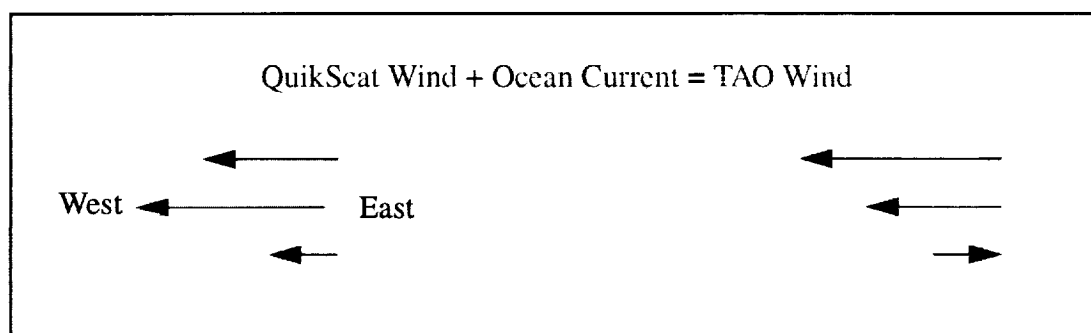
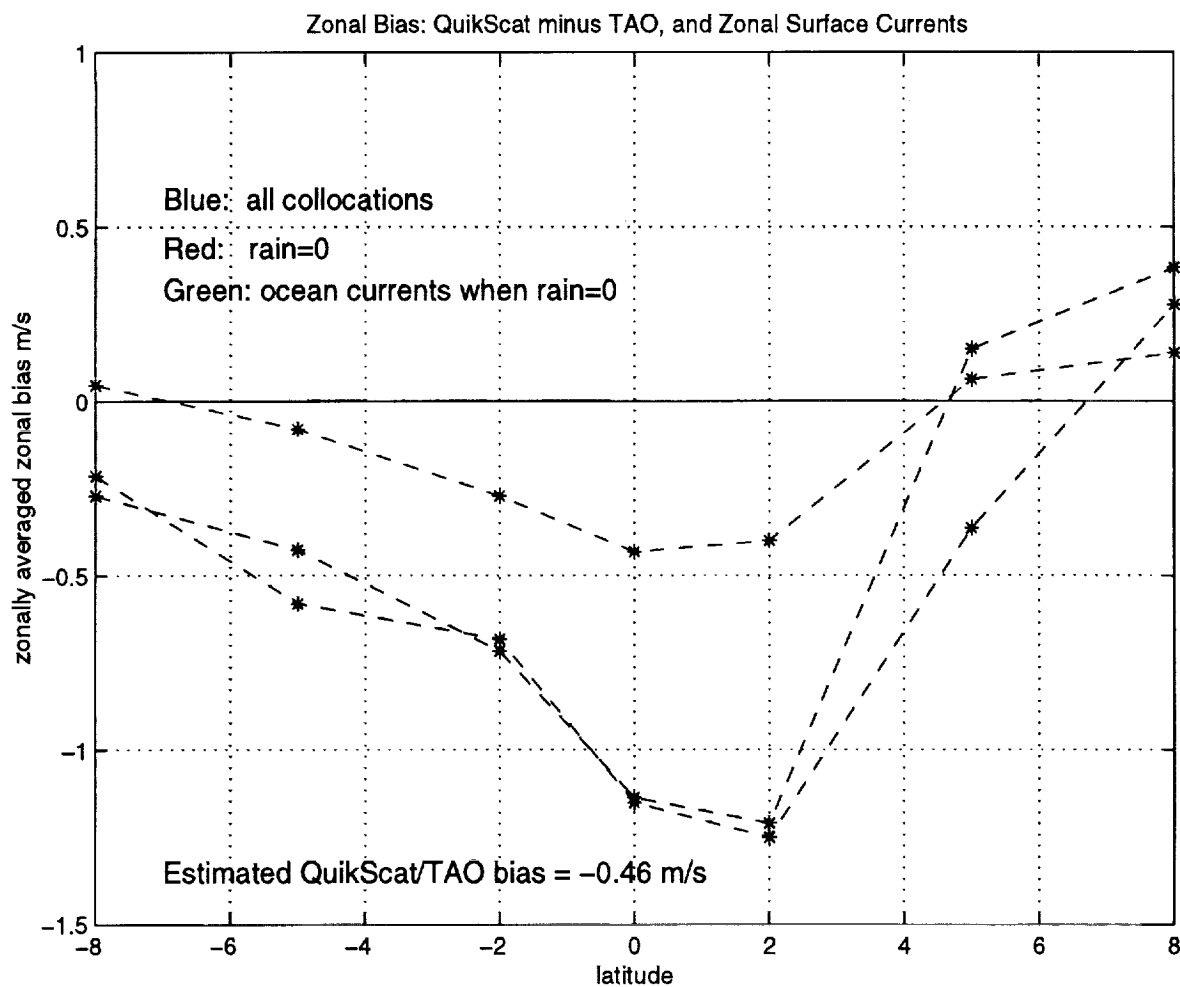


Figure 4: Normalized stress magnitude error $((\text{NSCAT2} - \text{TAO}) / \text{TAO})$ as a function of precipitation rate. The scatterplot includes monthly averaged data from buoys at 5°N and 8°N (the ITCZ region). The solid line is the best fit to the data and suggests that a precipitation rate of 10mm per day will cause about a 20% overestimate in stress. (Figure 5 from *A Note on Comparisons between the TAO Buoy and NASA Scatterometer Wind Vectors*.)

Kelly and Dickinson participated in the calibration/validation effort for QuikScat, again using hourly TAO data. Preliminary comparisons between the QuikScat data and TAO buoy winds suggested that the 10m winds using the preliminary model function were 0.5 m/s too low. This bias is substantially less than a simple comparison between anemometer winds and scatterometer winds would suggest. The bias was estimated by first subtracting the effect of the currents from the anemometer winds, based on our knowledge that ocean currents create a discrepancy between the two measurements, Figure 5.



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Figure 5: Zonally averaged zonal wind speed bias between QuikScat wind vectors and TAO hourly wind vectors converted to 10m. Blue dashed line shows bias when all collocations are used. Red dashed line shows bias with collocations when rain = 0. Green dashed line shows ocean currents developed with a method by Lagerlof, et al., 1999.

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Final Patents Report

There are were no patents registered for work done on this project.